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INVESTIGATION ON THE ABSORPTANCE OF STAINLESS STEEL  
TARGETS IRRADIATED BY A  $\text{Ti}:\text{Al}:\text{CO}_2$  LASER

J.-P. Morneau

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INVESTIGATION ON THE ABSORPTANCE OF STAINLESS STEEL

TARGETS IRRADIATED BY A TEA-CO<sub>2</sub> LASER

by

J.-P. Morency

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### RÉSUMÉ

Une méthodologie permettant de mesurer l'absorptance ( $\alpha$ ) de cibles métalliques soumises à l'irradiation d'un faisceau laser CO<sub>2</sub> TEA fait l'objet de la présente publication. L'approche expérimentale utilisée permet des mesures dynamiques du comportement de  $\alpha$  lorsque le faisceau laser est la seule source énergétique employée. La dépendance thermique des propriétés thermophysiques du matériau est une variable fondamentale dont notre analyse tient compte lors du traitement des résultats expérimentaux. On montre que l'oxydation superficielle du matériau accroît de façon non-linéaire et irréversible la quantité d'énergie rayonnante absorbée par la cible et ce, à partir d'un seuil thermique déterminé par le matériau utilisé et les conditions spécifiques de l'environnement où l'essai est effectué. (NC)

### ABSTRACT

A methodology has been developed to measure the absorptance ( $\alpha$ ) of metal targets irradiated by a TEA-CO<sub>2</sub> laser. The approach allows dynamic measurements of the behavior of  $\alpha$  when a laser beam is the sole heating source involved. Temperature-dependent thermophysical properties are considered in the reduction of the experimental data. It is shown that oxidation increases drastically the coupling of energy to the target above a threshold temperature which is a function of the type of material used and the environment into which the test is made. (U)

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## 1.0 INTRODUCTION

Laser irradiation of materials can induce high heating rates, produce chemical reactions and phase changes even to the extent of complete target vaporization. Duley (Ref. 1) presents a complete description of laser material interaction phenomena; other reviews are also available (Refs. 2 - 4).

In general, the thermal effects produced by laser radiation incident on a metal target are dependent on the absorptance  $\alpha$ , defined as

$$\alpha = \frac{\text{AVERAGE ENERGY ABSORBED}}{\text{AVERAGE ENERGY INCIDENT}} \quad [1]$$

This coefficient depends on the wavelength, the temperature and the conditions of the material surfaces; for pure metal surfaces it can be calculated, in the infrared part of the spectrum, from data on the metal resistivity (Refs. 1,5). It has been shown (Refs. 6-9) however, that the heating rate of metals by CW-CO<sub>2</sub> laser radiation is considerably increased in an oxidizing environment, like air, because of the growth of an oxide layer which favors absorption of the energy. The absorptance for laser radiation incident on metal surfaces, under conditions of surface erosion and oxidation, is consequently of paramount importance.

Section 2.0 of this report deals with the experimental procedure and the apparatus used while Section 3.0 presents the results of the absorptance measurements of stainless steel #304 irradiated by a TEA-CO<sub>2</sub> laser in the presence of air. The variation of  $\alpha$  due to oxidizing

reactions at the surfaces of the target is investigated. The absorptance is observed to increase by a factor of up to 5 or 6 from the initial value. In Section 4.0 appears a general discussion of our results.

This work was performed at DREV between January 1979 and September 1980 under PCN 33B06, Effects of Laser Beams on Materials.

## 2.0 EXPERIMENTAL PROCEDURE AND APPARATUS

The absorptance experiments on stainless steel #304 were performed in the DREV laser test facility shown schematically in Fig. 1. The high-repetition-rate TEA- $\text{CO}_2$  laser (HRRL), fully described elsewhere (Ref. 10), is an electrically excited closed gas circulation unit. Table I shows its basic physical properties while Table II gives its main operational characteristics.

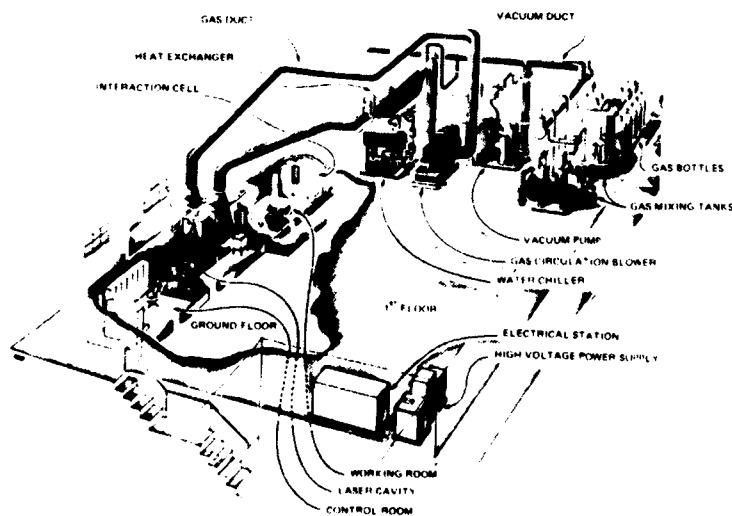


FIGURE 1 - High-repetition-rate TEA- $\text{CO}_2$  laser facility

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TABLE I

Basic physical properties of DREV  
high-repetition-rate TEA-CO<sub>2</sub> laser (HRRL) cavity

Mirror-window separation:	3.68 m
Total length of active medium:	1.95 m
Total width of active medium (cathode region):	3.25 cm
Interelectrodes gap:	2.5 cm
Cathode arrangement:	1220 resistively loaded pins on 5 bays of 46x6.5x3.1 cm
Anode arrangement:	5 Al plates with curved edges of 46x6.35x1.27 cm
Quasi semiconfocal stable cavity*:	$R_1 = \infty$ , $R_2 = 8$ m

\* The optical components are supported by elevation over azimuth gimbal mounts having a total angular travel in both directions of 24 mrad with an accuracy and a repeatability of  $\pm 0.2$  mrad. These mounts are remotely controlled by 500 steps/r stepping motors.

TABLE II

HRRL main operational characteristics

Gas composition	Electrical Input	Laser beam
He + 80%	Frequency: 0.1 - 1000 Hz	Dimensions (Output window): 2x3.5 cm
3% + CO <sub>2</sub> + 10%	Voltage range: 0 - 35 kV	Total vertical divergence: $\theta_v = 4.5$ mrad
5% + N <sub>2</sub> + 15%	Discharge length: $\approx 0.5$ $\mu$ s	Total horizontal divergence: $\theta_H = 7.5$ mrad
Pressure range: 10 - 134 kPa	Peak voltage: $\approx 50$ kV	Total energy: 1.5 - 3 J/pulse
Flow rate: 0 - 3000 l/s	Peak current: $\approx 10,000$ A	Total pulse length: 2-25 $\mu$ s
Gas speed (cavity): 0-35 m/s	Total energy: $\approx 50$ J/pulse	FWHA peak: 0.5-1 $\mu$ s
Gas temperature (cavity) Input: $\approx 300$ K Output: variable with the frequency of operation	Energy loss in resistively loaded pins: $\approx 5$ J/pulse	Average power: 0.3 W - 1.5 kW Peak power: 0.5-5 MW Wavelength: 10.6 $\mu$ m



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The laser beam produced by the HRRL is directed into an interaction cell, which may be evacuated to about 0.5 torr ( $\sim 50$  Pa), and focused on the metal target under investigation. Figure 2 shows a layout of the experimental setup used. Some characteristics of this setup are fundamental to our calorimetric approach: the transversal dimensions of the target have to be equal or slightly larger than the size of the laser beam and the flux must be as constant and uniform as possible on the target surface. Furthermore, our experimental procedure requires a time reference, since our process is dynamic and time dependent, and a common link to an HP-3052 data acquisition system (DAS) for all apparatus and devices. This DAS controls and monitors all experimental phases; similarly, it reduces, saves and displays data.

Our targets, punched from a large sheet of material, are not submitted to any special cleaning process before being used. They have an rms surface finish five to ten times smaller than the laser wavelength used ( $10.6 \mu\text{m}$ ). Because of this, no effect is expected from the roughness of the surface.

A CRL Model 213 water-cooled power meter, having an absolute accuracy of  $\pm 10\%$ , is used to monitor the fraction of the power reflected by the NaCl beam splitter.

Two 30-gauge chromel-alumel thermocouples are spot-welded to the rear surface of the sample. Then, the target is installed and positioned with its two supporting thermocouples. The positioning is done according to a burn pattern produced by the HRRL, operating at 0.5 to 1 Hz, on a piece of thermosensitive paper. Rectangular targets are used because the multiline or multimode laser is rectangular with its vertical dimension being about half the horizontal one. Figure 3 shows the sequence of events for a typical test.

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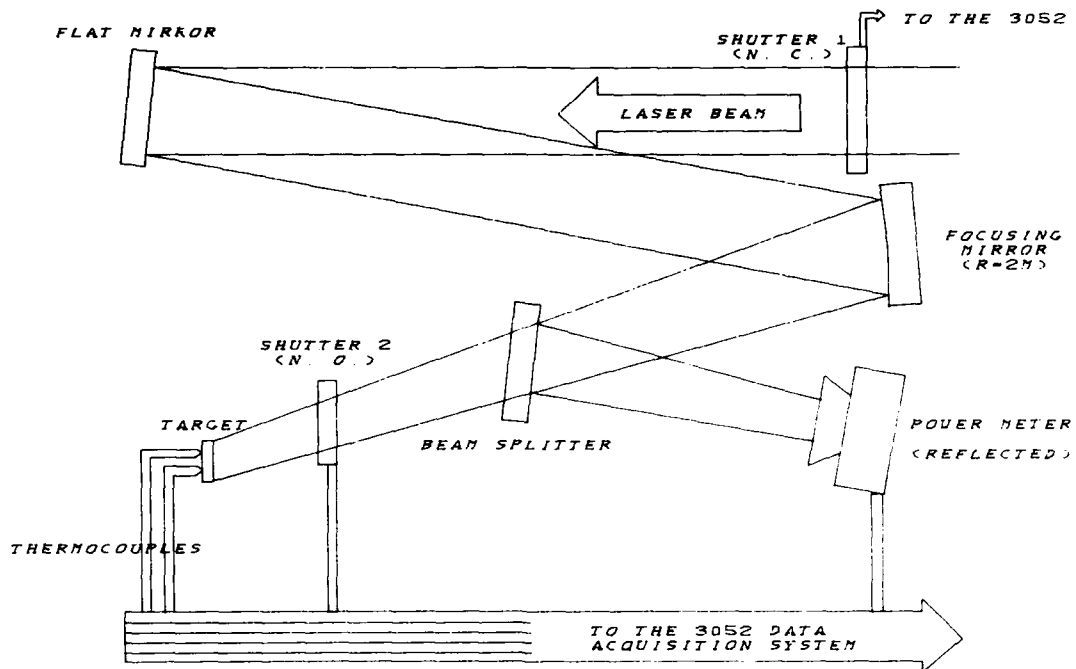


FIGURE 2 - Layout of the experimental setup

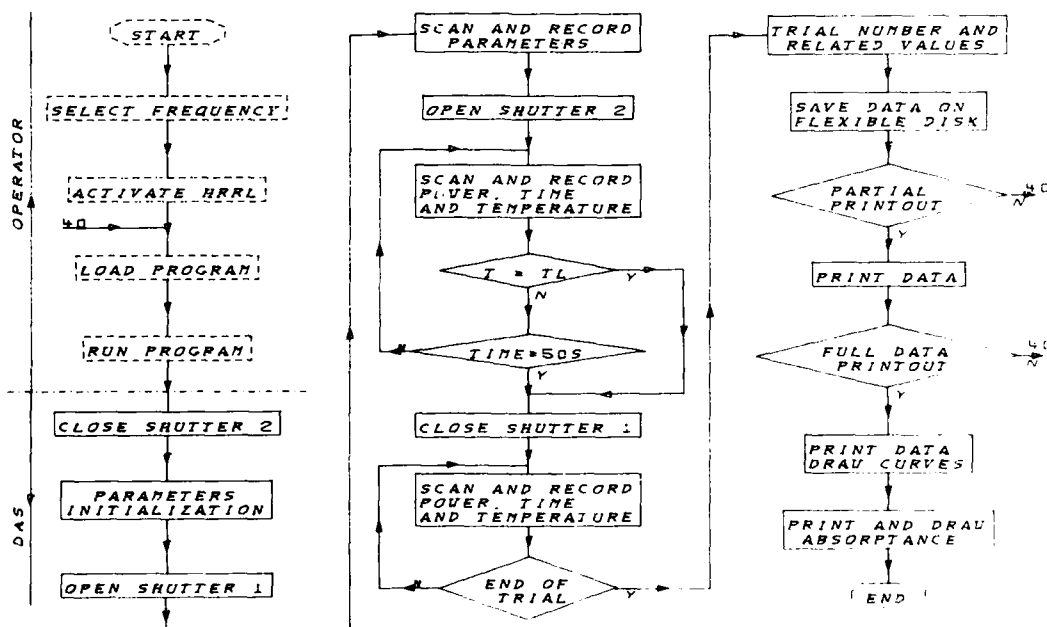


FIGURE 3 - Flowchart of a typical experiment

The DAS instrumentation includes an HP-9825A calculator-controller unit with 24 KBytes of RAM (in fact, around 21.8 KBytes when all the ROMs and the related devices are plugged in), an HP-3495A 40-channel electronic scanner with low-level thermal relays, an HP-3455A digital voltmeter for high-accuracy measurement, an HP-3437A system voltmeter for high-speed reading, an HP-IB general-purpose interfacing bus (IEEE 488-1975), an HP-1350A graphics translator and a CRT for rapid visualization of the results, an HP-9871A character-impact printer with HP-IB programming for hard copy of results, a real-time clock with an optional external trigger, an HP-9885M master flexible disk drive and some other related devices and apparatus not used for these tests.

### 3.0 RESULTS

A typical pulse shape measured with a photon-drag detector appears in Fig. 4. Figure 5 shows typical curves of the temperature as a function of time for the experimental sequence defined in Fig. 3. A different symbol is used for each thermocouple curve. The laser beam heats the sample up to a preselected temperature ( $T_L$ ) or time (50 s), whichever comes first. Then, shutter 1 closes and the specimen cools off. Acquisition of temperature data goes on until the 9825A-controller memory is full and then it stops. From these experimental data, it is possible to determine the absorptance ( $\alpha$ ).

The relation between the rate of temperature increase and the amount of energy input is provided by the heat-diffusion equation which, in our case, is simplified to the following calorimetric form.

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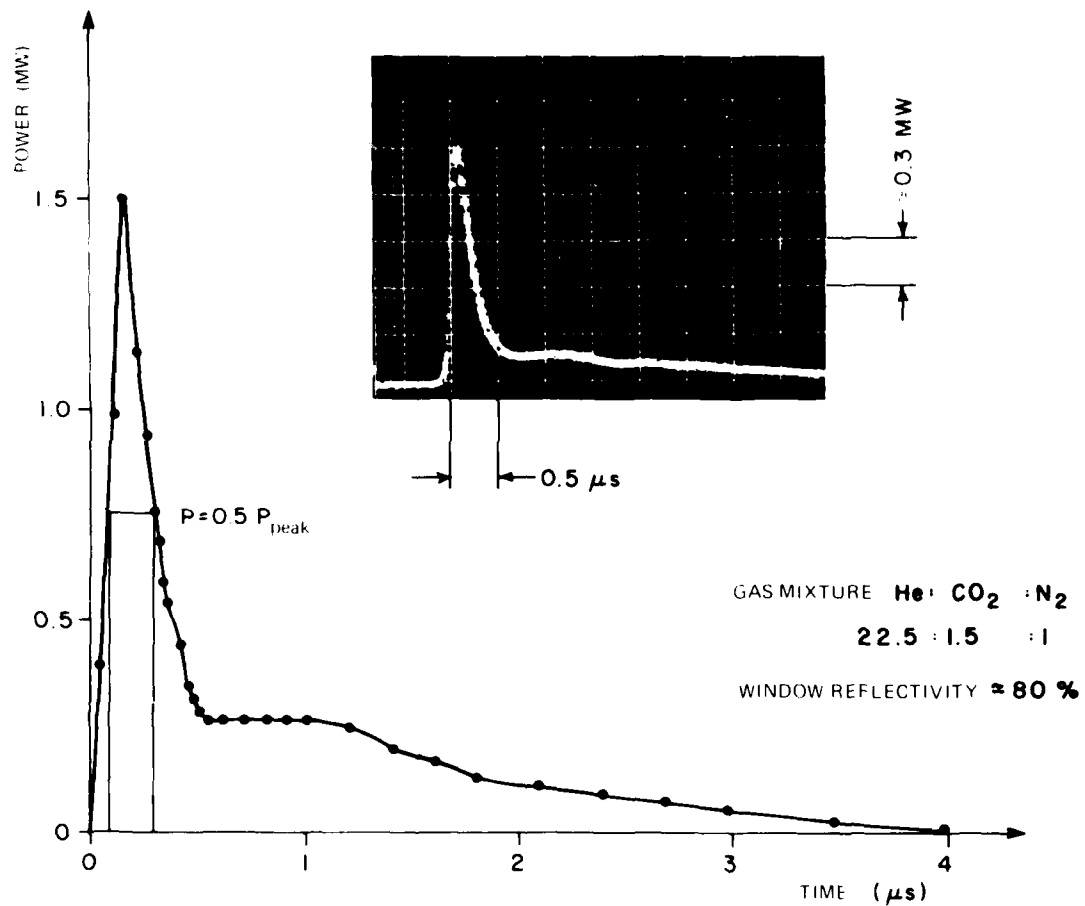


FIGURE 4 - Typical laser pulse shape

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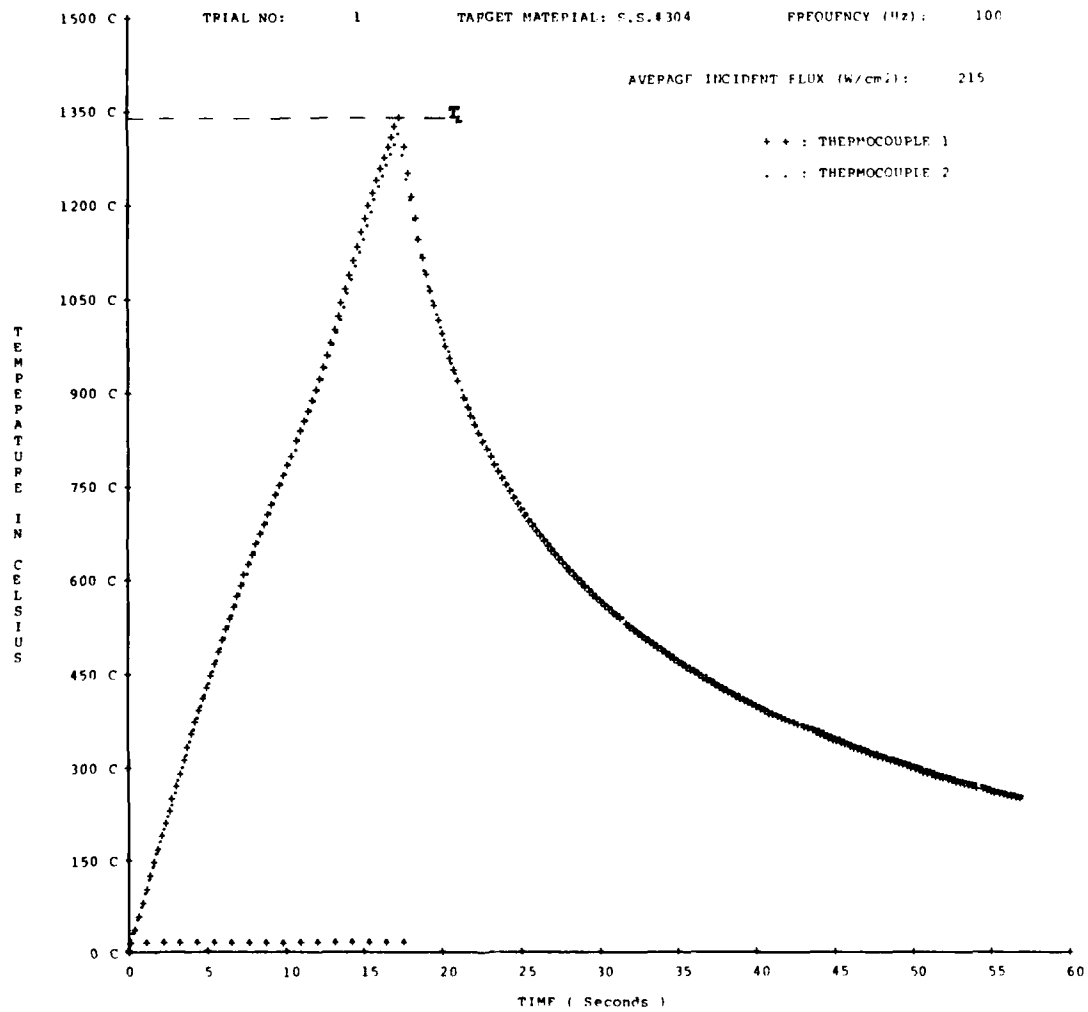


FIGURE 5 - Target temperature vs time for the specified conditions

$$\rho \cdot C_p(T) \cdot l \cdot s \cdot \left( \frac{\Delta T}{\Delta t} \right)_{\text{heating}} = \alpha(T) \cdot P_{\text{av}} - P_L(T) \quad [2]$$

where  $\rho$ ,  $C_p(T)$ ,  $l$ ,  $s$ ,  $\left( \frac{\Delta T}{\Delta t} \right)_{\text{heating}}$ ,  $\alpha(T)$ ,  $P_{\text{av}}$  and  $P_L(T)$  are respectively the density, the temperature-dependent specific heat at constant pressure, the material thickness, the area of interaction, the heating rate, the absorptance, the average incident power and the average power lost by the specimen as a function of the temperature  $T$ . Thermophysical properties and their variation with temperature are extracted from handbook data (Ref. 11). Only temperature-dependent heat losses are considered in our analysis (i.e. convective and radiative ones); other heat losses are negligible.

The heat losses can be estimated by measuring the cooling rates of the specimen from a fixed temperature  $T$ . They take the following form

$$\rho \cdot C_p(T) \cdot l \cdot s \cdot \left( \frac{\Delta T}{\Delta t} \right)_{\text{cooling}} = -P_L(T). \quad [3]$$

Substituting [3] into [2] and rearranging the terms gives

$$\alpha(T) = \frac{\rho \cdot C_p(T) \cdot l \cdot s}{P_{\text{av}}} \left[ \left( \frac{\Delta T}{\Delta t} \right)_{\text{heating}} - \left( \frac{\Delta T}{\Delta t} \right)_{\text{cooling}} \right]. \quad [4]$$

This equation requires the determination of heating and cooling rates from the sample temperature curves as a function of time. Figure 6 shows a typical set of heating and cooling rate curves. The heating rates are positive while the cooling ones are negative such that subtracting them, for a given temperature, gives the term within brackets of eq. 4. Temperatures on the vertical axis are the averaged ones over the temperature intervals considered.  $C_p(T)$  and  $\alpha(T)$  correspond to those same temperatures while the power is monitored and averaged over the heating part of the cycle to get  $P_{av}$ .

Figure 7 shows the absorptance as a function of the temperature calculated from the data of Fig. 6. Two different symbols are used to plot the curves originating from each thermocouple. These curves start at the lowest temperature recorded during the cooling part of the cycle. A nonuniform intensity distribution of the laser beam on the target surface could explain the noncoincidence of the two curves. It shows that the absorptance of stainless steel #304 in standard environment (air at atmospheric pressure) increases steadily, in a nonlinear manner, with the temperature.

Oxidation of the surfaces is the mechanism responsible for the variation of the absorptance. The reproducibility of our results with stainless steel #304, as shown in Fig. 8, indicates that the same oxidation process repeats itself systematically for a set of given specific operational conditions. The buildup of an oxide layer is a very complex phenomenon, specially in a dynamic process like the present one; however, a correlation with a simple model could be worthwhile in understanding the basic parameters involved.

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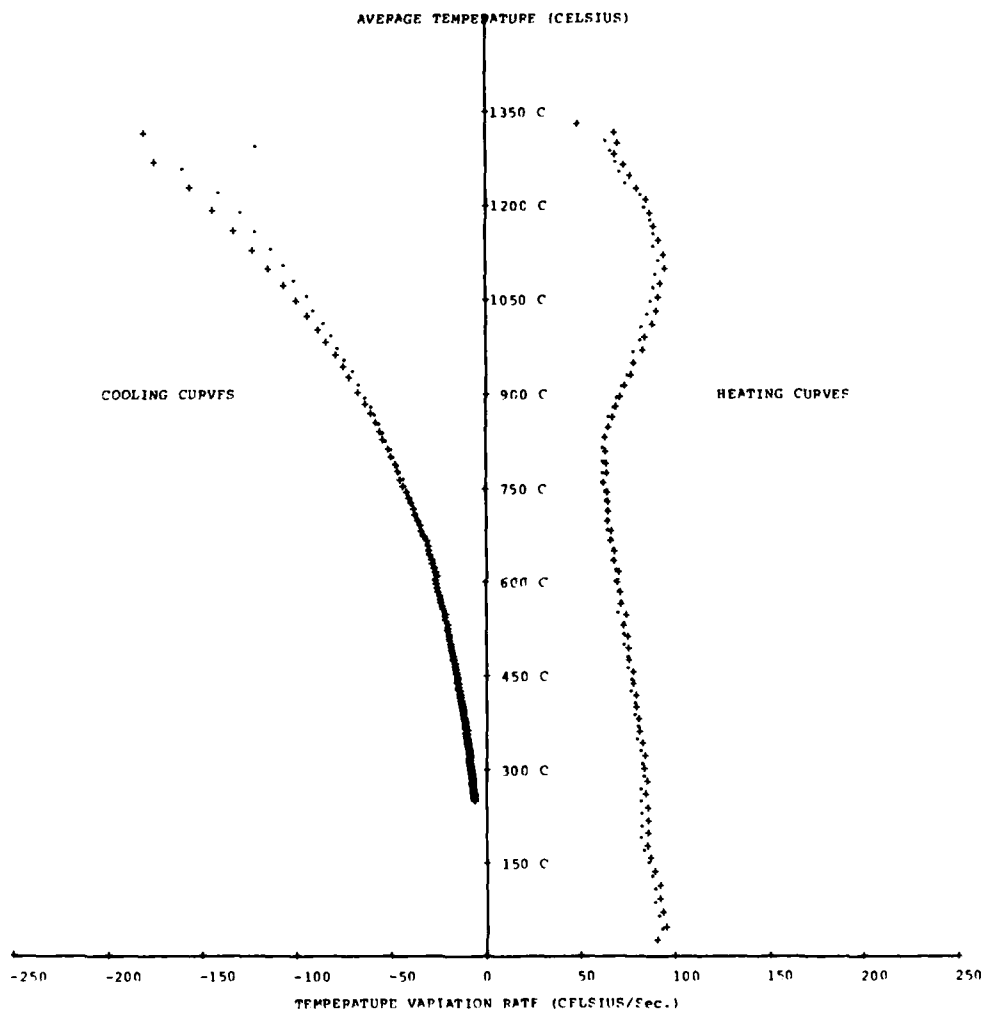
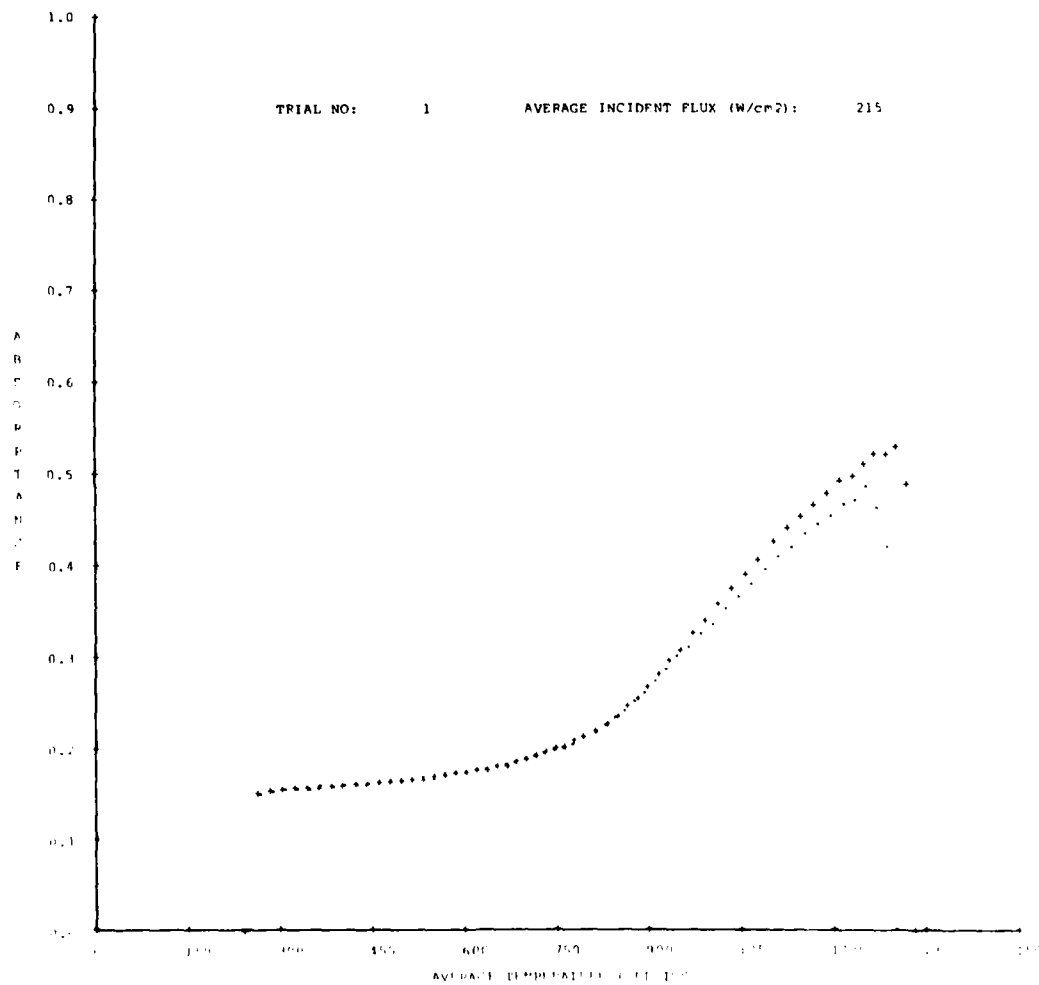


FIGURE 6 - Target heating and cooling rates obtained from Fig. 5



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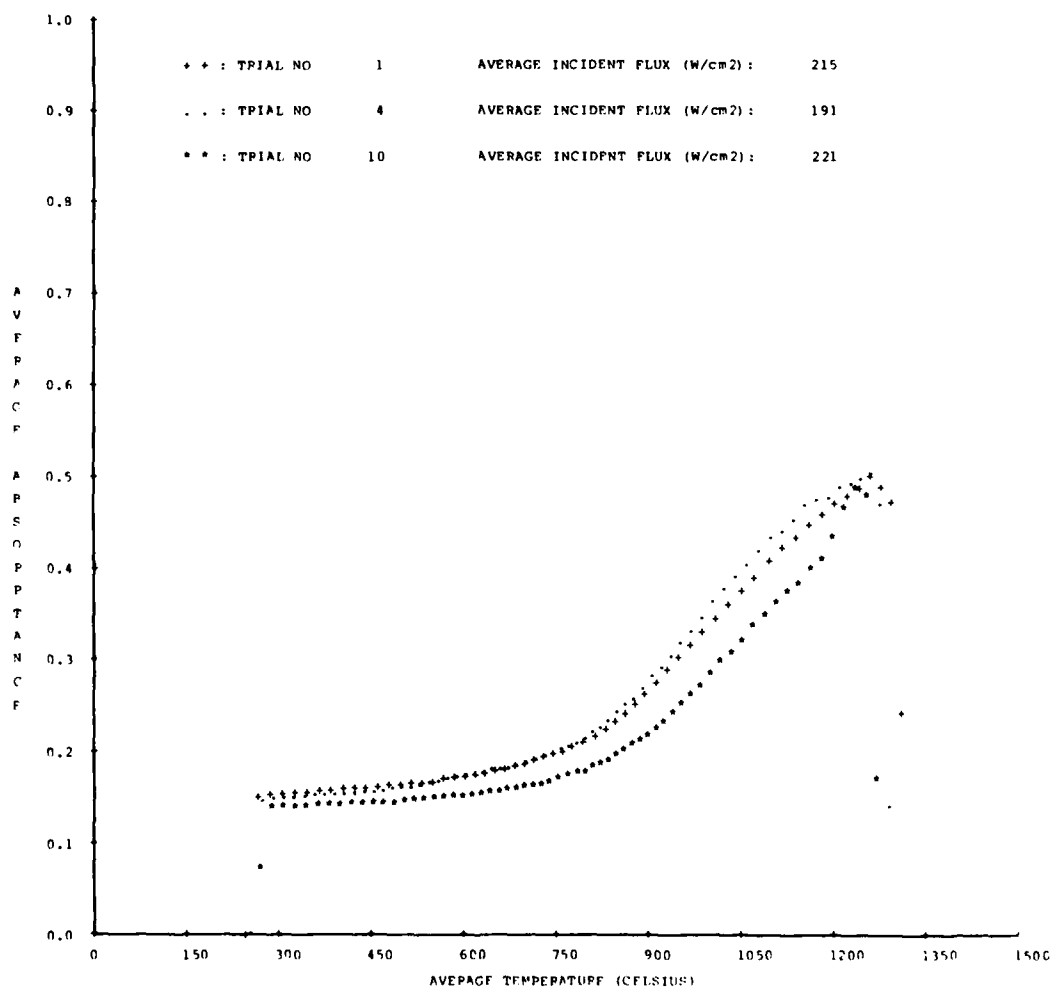


FIGURE 8 - Average absorptance vs temperature for three incident fluxes

#### 4.0 DISCUSSION OF RESULTS

The uniformity of the laser-beam irradiation over the target surface can be estimated by the coincidence of both curves of temperature as a function of time. As temperature gets higher and the nonlinear effects of surface oxidation becomes important, a discrepancy between the readings of the two thermocouples then appears. To understand this behavior, we have to remember that our laser beam is a multimode one with two side-lobes having peak amplitudes above the normalised average one. Consequently, small spatial perturbations in the intensity are likely present.

The temperature variations of the specific heat,  $C_p(T)$ , has a direct influence on the absorptance [eq. 4]: for stainless steel #304, the specific heat and, consequently, the related absorptance increase by a factor 1.5 from room to melting temperature. This effect can be easily pinpointed at low temperatures where no other mechanism like oxidation is contributing significantly. This explains that we do not have a straight horizontal behavior for the temperature curves at low temperatures.

Conduction losses through the thermocouple leads is an effect not accounted for in our determination of the absorptance. We evaluate the maximum error introduced by those losses to be around 3% in our present setup.

The use of a pulsed laser instead of a CW one has certainly a considerable impact on the time-temperature distribution throughout the target thickness, specially when high-average temperatures and a large value of the absorptance due to oxidation are present simultaneously. A calculation for a step-function heat pulse appears in Appendix A. Incident surfaces can be heated up to and above the melting temperature

of the material for a short-time duration before being cooled down through heat conduction within the material, radiation and convection to the environment. This phenomenon may explain why we do not have a sharp threshold value for the initiation of the oxidation effect as found with similar experiments using a CW source.

### 5.0 CONCLUSIONS

We have developed a methodology to dynamically measure the absorptance of metal targets with a TEA-CO<sub>2</sub> laser as the sole source of irradiation. A simple model, based on the calorimetric equation, was used to interpret the results: this showed that two parameters were quite critical in our experiments. These were the uniformity of the energy distribution on the target and the alignment of the laser beam to cover the total surface of the target without extending over the edges. The programmable data acquisition system (DAS) was quite an asset for the storing, the reduction, the correlation, the analysis and the presentation of our results.

We have showed the drastic effect of oxidation on the absorptance of stainless steel #304 heated in a standard environment. From a threshold temperature, depending on the type of material used and the environment in which the test is made, an oxidation coating starts to build up on the sample surfaces. This phenomenon increases the initial value of the absorptance by a factor of up to 5 or 6. Our approach can be used with any other type of nonablative materials for which thermophysical properties are well-known.

### 6.0 ACKNOWLEDGEMENTS

The author thanks Mr. R. Gosselin for his expert technical assistance in performing the experiments. Gratitude is also expressed to Dr. M. Gravel and Dr. R. Carboneau for many helpful discussions.

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APPENDIX A

Assuming a spatially uniform laser beam having a top hat temporal shape irradiating a semi-infinite solid target, the one-dimensional heat conduction solution has the following form

$$T(z,t) = \frac{2 \cdot \phi \cdot \sqrt{\kappa \cdot t}}{K} \cdot \text{ierfc } z/(2 \cdot \sqrt{\kappa \cdot t}) \text{ for } 0 \leq t \leq t_p \quad [A1]$$

where  $z$ ,  $t$ ,  $t_p$ ,  $T(z,t)$ ,  $\phi$ ,  $\kappa$ ,  $K$  and  $\text{ierfc}$  are respectively the depth, the time, the pulse length, the temperature, the absorbed flux, the thermal diffusivity, the thermal conductivity and the integral of the complementary error function.

The front-surface temperature behavior is obtained by putting  $z = 0$  in [A1] so that

$$T(0,t) = \frac{2 \cdot \phi \cdot \sqrt{\kappa \cdot t}}{K} \text{ for } 0 \leq t \leq t_p \quad [A2]$$

Within our operational conditions, the preceding equations are valid for times smaller than 50 ms.

Since our targets are made of stainless steel we use  $K \sim 0.26$  W/cm<sup>2</sup>°C and  $\kappa \sim 0.05$  cm<sup>2</sup>/s. Results of typical calculations appear in Table A1.

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TABLE AI

Front-surface temperature ( °C) of a stainless steel target  
irradiated by a top hat laser pulse

Pulse length (microseconds)			
	0.1	0.2	0.5
Absorbed Flux (MW/cm <sup>2</sup> )			
0.1	54	77	122
0.2	109	154	245
0.5	272	375	610

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"Investigation on the Absorbance of Stainless Steel Targets Irradiated"  
by a TEA-CO<sub>2</sub> Laser" by J.P. Morency

A methodology has been developed to measure the absorbance ( $\alpha$ ) of metal targets irradiated by a TEA-CO<sub>2</sub> laser. The approach allows dynamic measurements of the behavior of  $\alpha$  when a laser beam is the sole heating source involved. Temperature-dependent thermophysical properties are considered in the reduction of the experimental data. It is shown that oxidation increases drastically the coupling of energy to the target above a threshold temperature which is a function of the type of material used and the environment into which the test is made. (U)

DREV R-4232/82 (UNCLASSIFIED)

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